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(54) Stencilling phosphor layers on light emitting diodes

(57) A method for forming a luminescent layer on a light emitting semiconductor device includes positioning a stencil on a substrate such that a light emitting semiconductor device disposed on the substrate is located within an opening in the stencil, depositing a stencilling composition including luminescent material in the opening, removing the stencil from the substrate, and curing the stencilling composition to a solid state. The resulting

light emitting device includes a stack of layers including semiconductor layers comprising an active region and a luminescent material containing layer having a substantially uniform thickness disposed around at least a portion of the stack. A surface of the luminescent material containing layer not adjacent to the stack substantially conforms to a shape of the stack. In one embodiment, the light emitting device emits white light in a uniformly white spatial profile.

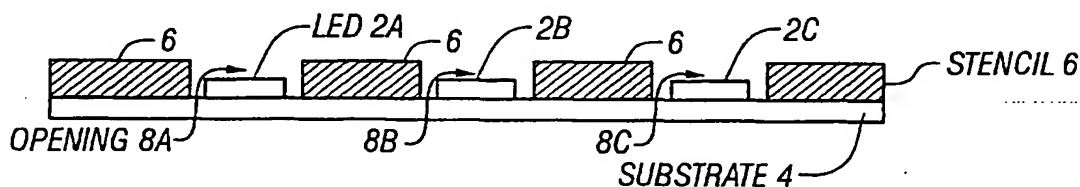


FIG. 3A

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## Description

### BACKGROUND OF THE INVENTION

#### 1. Field of the Invention

[0001] The present invention relates generally to light emitting devices and more particularly to light emitting diodes using phosphors.

#### 2. Description of the Related Art

[0002] Blue light emitting diodes (LEDs) are used with luminescent materials (phosphors) to produce light emitting devices which emit apparently white light. U.S. Patents 5,813,753 and 5,998,925, for example, disclose light emitting devices in which a blue LED is disposed in a reflective cup and surrounded by material including phosphors. A portion of the blue light emitted by the LED is absorbed by the phosphors, which in response emit red and green light. The combination of the unabsorbed blue light emitted by the LED and the red and the green light emitted by the phosphors can appear white to the human eye. Unfortunately, such conventionally phosphor surrounded LEDs frequently emit white light in a central cone surrounded by annular rings of yellow and blue light, rather than emit light in a uniformly white spatial profile.

[0003] Lowery U.S. Patent 5,959,316, incorporated herein by reference, discloses that such annular rings of blue and yellow light can result from nonuniformity in the thickness of the phosphor containing material surrounding the LED and consequent spatially nonuniform absorption of blue light and emission of red and green light. In particular, thick regions of phosphor containing material absorb more blue light and emit more red and green light than do thin regions of phosphor containing material. The thick regions thus tend to appear yellow, and the thin regions tend to appear blue. Lowery also discloses that deposition of a transparent spacer over and around the LED prior to deposition of a uniform thickness of phosphor containing material can eliminate the annular rings in the emission profile. However, surface tension makes the shape and thickness of the phosphor containing material, typically deposited as a liquid or paste (solids dispersed in a liquid), difficult to control.

[0004] What is needed is a method for uniformly coating an LED with phosphor containing material.

#### SUMMARY

[0005] A method for forming a luminescent layer on a light emitting semiconductor device includes positioning a stencil on a substrate such that a light emitting semiconductor device disposed on the substrate is located within an opening in the stencil, depositing a stenciling composition including luminescent material in the open-

ing, removing the stencil from the substrate, and curing the stenciling composition to a solid state. In one embodiment, the shape of the opening in the stencil substantially conforms to the shape of the light emitting semiconductor device, the depth of the opening is about equal to a sum of a height of the light emitting semiconductor device and a thickness of the luminescent layer, and a width of the opening is about equal to a sum of a width of the light emitting semiconductor device and twice a thickness of the luminescent layer.

[0006] In one embodiment, the stencil is positioned such that each one of a plurality of light emitting semiconductor devices disposed on the substrate is located within a corresponding one of a plurality of openings in the stencil. Stenciling composition is deposited in each of the openings.

[0007] Luminescent layers are formed on light emitting semiconductor devices without contaminating adjacent areas of the substrate and without completely covering, for example, substrate electrical contacts. Thus, wire bonding of such contacts can occur subsequent to the formation of the luminescent layers. In addition, since many light emitting devices can be disposed on a single substrate and simultaneously stenciled with luminescent material containing layers, this method results in a high throughput and is thus cost effective.

[0008] In one embodiment, the luminescent stenciling composition includes phosphor particles and silica particles dispersed in an optically clear silicone polymer which can be cured by heat or light. Preferably, the uncured silicone polymer has a viscosity between about 1000 centistokes and 20000 centistokes and the silica particles are fumed silica particles having a surface area per unit mass greater than about 90 m<sup>2</sup>/g. The silica particles employed in this embodiment impart thixotropic properties to the luminescent stenciling composition. As a result, a layer formed from the uncured luminescent stenciling composition retains its shape after stenciling without collapsing or slumping. Once cured to a solid state, a layer formed from the luminescent stenciling composition exhibits sufficient strength to withstand subsequent processing of the light emitting semiconductor device on which it is formed. In addition, a cured layer of the luminescent stenciling composition formed in accordance with this embodiment is chemically and physically stable at temperatures in excess of 120°C. In particular, the cured layer of luminescent stenciling composition will not yellow during prolonged exposure to temperatures between about 120°C and about 200°C.

[0009] A resulting light emitting device includes a stack of layers including semiconductor layers comprising an active region and a luminescent material containing layer having a substantially uniform thickness disposed around at least a portion of the stack. A surface of the luminescent material containing layer not adjacent to the stack substantially conforms to a shape of the stack. In one embodiment, the light emitting device includes, in addition, an optically transparent layer dis-

2 lack such wirebond connections to their top surfaces, they are more easily stenciled with phosphor containing material.

[0017] Referring again to Figure 1, stencil 6 is positioned on substrate 4 such that openings 8A-8F are aligned with LEDs 2A-2F and bottom surface 7 of stencil 6 is in contact with top surface 3 of substrate 4. As shown in the side view of stencil 6 positioned on substrate 4 illustrated in Figure 3A, LEDs 2A-2C, for example, are located approximately centered in corresponding openings 8A-8C in stencil 6. Next, a curable luminescent stenciling composition, such as the phosphor containing stenciling composition described below, is disposed in openings 8A-8F in stencil 6. In one implementation, the stenciling composition is disposed in openings 8A-8F of stencil 6 with a metal blade drawn across surface 5. Stencil 6 is then removed from substrate 4, leaving stenciled phosphor layers, such as phosphor layers 30A-30C illustrated in Figures 3B and 3C, disposed over and around LEDs 2A-2F.

[0018] In one implementation, the steps of positioning stencil 6 on substrate 4, disposing a luminescent stenciling composition on surface 5 and in openings 8A-8F to form phosphor layers such as phosphor layers 30A-30C on LEDs 2A-2F, and removing stencil 6 from substrate 4 are performed by a conventional high precision stenciling machine typically used to stencil solder paste onto printed circuit boards. The stenciling machine is, for example, an Ultraprint 1500 manufactured by MPM Corporation of Franklin, Massachusetts.

[0019] After stencil 6 is removed from substrate 4, the phosphor layers on LEDs 2A-2F are cured to a solid state by, for example, application of heat or ultraviolet radiation. The curing process can involve, for example, cross-linking of polymeric material in the phosphor layers. In one implementation, LEDs 2A-2C, for example, are heated to about 100°C in a conventional oven for about 10 minutes to cure phosphor layers 30A-30C.

[0020] The resulting LED 2A, for example, having phosphor layer 30A in accordance with one embodiment is schematically illustrated in Figure 4. Phosphor layer 30A has a substantially uniform thickness above top surface 32 and adjacent to vertical sides 34 and 36 of LED 2A. Also, top surface 38 and vertical side surfaces 40 and 42 of phosphor layer 30A are substantially parallel to top surface 32 and vertical side surfaces 34 and 36, respectively, of LED 2A. Thus, outer surfaces of phosphor layer 30A, such as surfaces 38, 40, and 42, substantially conform to the shape of LED 2A. Dimensions of phosphor layer 30A denoted A and B both range from about 50 microns ( $\mu\text{m}$ ) to about 250  $\mu\text{m}$ .

[0021] After the phosphor layers on LEDs 2A-2F are cured, substrate 4 is sawn or scribed to separate LEDs 2A-2F into discrete devices (dice).

[0022] In one embodiment, LEDs 2A-2F having conforming phosphor layers 30A-30F of substantially uniform thickness emit light in a uniformly white spatial profile. In particular, the yellow and blue annular rings of

conventionally phosphor surrounded white light devices are eliminated. Moreover, phosphor layers 30A-30F can be disposed on LEDs 2A-2F without contaminating adjacent areas of substrate 4 and without completely covering substrate contacts such as contacts 26 and 28 of LED 2A. Thus, wire bonding of, for example, contacts 26 and 28 can occur subsequent to the formation of phosphor layer 30A. In addition, since many LEDs can be disposed on a single substrate and simultaneously stenciled with phosphor layers, the stenciling process described above is a high-throughput and cost effective process.

[0023] The phosphor layers on LEDs 2A-2F must substantially retain their stenciled shapes, without collapsing or slumping, until cured. In addition, it is desirable that the phosphor layers withstand operating temperatures exceeding about 120°C for long periods of time without change in their chemical or physical properties. Epoxies, urethanes, and similar organic resins, for example, are unsuitable for use in the phosphor layers, because at temperatures exceeding about 120°C they oxidize and become yellow. The yellow organic resins then absorb blue light emitted from the LED, degrading the performance of the device. The apparent color of a device intended to emit white light, for example, would shift toward yellow as the organic resins oxidized.

[0024] A luminescent stenciling composition suitable for use in accordance with an embodiment of the present invention is prepared as follows. First, a phosphor powder is mixed with a conventional curable silicone polymer composition. The curable silicone polymer composition includes at least one polymer having a chemical structure that includes alternating silicon and oxygen atoms (a silicone polymer), and optionally includes a curing agent such as a catalyst that catalyzes cross-linking of silicone polymers or a photopolymerization initiator. The curable silicone polymer composition is preferably substantially nonabsorbing and nonscattering (optically clear) for wavelengths of light from about 400 nm to about 600 nm. The uncured stenciling composition should have a viscosity greater than about 1,000 centistokes if it is to retain its stenciled shape until it is cured, and if the phosphor particles are to remain in suspension rather than sediment out, but less than about 20,000 centistokes if it is to be easily stenciled. Consequently, the curable silicone polymer composition preferably has a viscosity, before curing, of about 1,000 centistokes to about 20,000 centistokes. In addition, the curable silicon polymer composition preferably has a refractive index greater than about 1.45, in order to increase the efficiency with which light is coupled out of the LED and out of the phosphor particles into the stenciling composition. Also, the curable silicone polymer composition is preferably stable as a liquid at room temperature until cured to a solid state by, for example, heating or exposure to ultraviolet light.

[0025] Suitable curable silicone polymer compositions are commercially available. In one implementa-

[0032] As in the schematic illustration of Figure 4, phosphor layer 30A in Figure 5 is of substantially uniform thickness and substantially conforms to the shape of LED 2A. In particular, top and side surfaces 38, 40 and 42 of phosphor layer 30A are substantially parallel to top and side surfaces 32, 34, and 36, respectively, of LED 2A. In addition, phosphor layer 30A in Figure 5 exhibits bulge 44 and tail 46 which form as or after the stencil is removed but before the luminescent stenciling composition is cured. Dimensions denoted by letters A-E are: A ~90  $\mu\text{m}$ , B ~60  $\mu\text{m}$ , C ~30  $\mu\text{m}$ , D ~80  $\mu\text{m}$ , E ~1.31 millimeters (mm). Dimensions A-E are typically reproducible to  $\pm 5\%$ . Dimension B is reproducible to  $\pm 2\%$ ,  $\pm 12 \mu\text{m}$  overall, if the stenciling process is implemented with a stenciling machine equipped with automatic pattern recognition software.

[0033] The concentration and grade of fumed silica used in the stenciling composition from which phosphor layer 30A illustrated in Figure 5 was formed were chosen to minimize bulge 44 and tail 46. If the concentration of fumed silica in the stenciling composition were increased, then the height of bulge 44 would increase and the length of tail 46 would decrease. Alternatively, if the concentration of fumed silica were decreased, then the height of bulge 44 would decrease, the length of tail 46 would increase, and sides 40 and 42 of phosphor layer 30A would slump such that dimension B was much smaller near top 32 of LED 2A than near substrate 4, and dimension A was much smaller near the edges of top 32 than near the center of top 32.

[0034] Referring to Figure 6, in another embodiment an optically transparent layer 48 is deposited on and around LED 2A, for example, prior to the deposition of stenciled phosphor containing layer 30A. In one implementation, optically transparent layer 48 is formed using the stenciling process discussed above from an optically transparent stenciling composition. A suitable optically transparent stenciling composition is prepared in essentially the same manner as the luminescent stenciling composition described above, but without the addition of phosphor particles. Optically transparent layer 48 has a thickness of about 45  $\mu\text{m}$  to about 80  $\mu\text{m}$ . Both optically transparent layer 48 and phosphor containing layer 30A are of substantially uniform thickness and substantially conform to the shape of LED 2A.

[0035] While the present invention is illustrated with particular embodiments, the invention is intended to include all variations and modifications falling within the scope of the appended claims. For example, the luminescent stenciling composition can include semiconductor nanocrystals and/or dye molecules in addition to or instead of phosphor particles.

#### Claims

1. A light emitting device comprising:

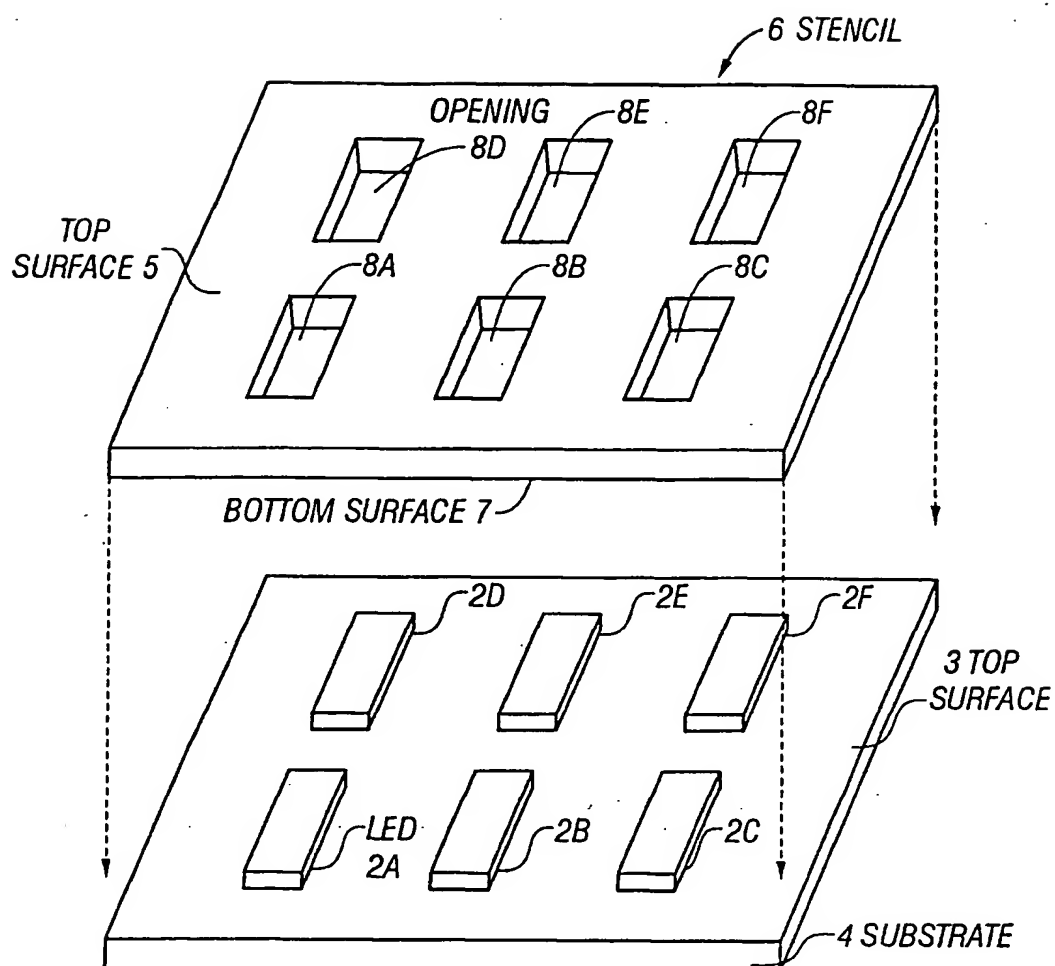
a stack of layers including semiconductor layers comprising an active region; and  
a luminescent material containing layer having a substantially uniform thickness disposed around at least a portion of said stack;

wherein a surface of said luminescent material containing layer not adjacent to said stack substantially conforms to a shape of said stack.

2. The light emitting device of Claim 1, wherein said luminescent material containing layer comprises at least one silicone polymer.
3. The light emitting device of Claim 1, wherein said luminescent material containing layer comprises silica particles.
4. The light emitting device of Claim 3, wherein said silica particles are fumed silica particles.
5. The light emitting device of Claim 1, wherein said luminescent material containing layer comprises phosphors that convert light of a wavelength emitted by said active region to at least another wavelength.
6. The light emitting device of Claim 5, wherein said phosphors comprise yttrium aluminum garnet doped with gadolinium and cerium.
7. The light emitting device of Claim 1, wherein said active region emits blue light, and wherein said luminescent material containing layer includes phosphors that convert a portion of said blue light to light combinable with a remaining portion of said blue light to produce white light.
8. The light emitting device of Claim 1, further comprising an optically transparent layer disposed between said luminescent material containing layer and said stack.
9. A light emitting device comprising:

a stack of layers including semiconductor layers comprising an active region; and  
a luminescent material containing layer having a substantially uniform thickness disposed around at least a portion of said stack, said luminescent material containing layer comprising a silicone polymer, fumed silica particles, and phosphors;

wherein a surface of said luminescent material containing layer not adjacent to said stack substantially conforms to a shape of said stack.



**FIG. 1**

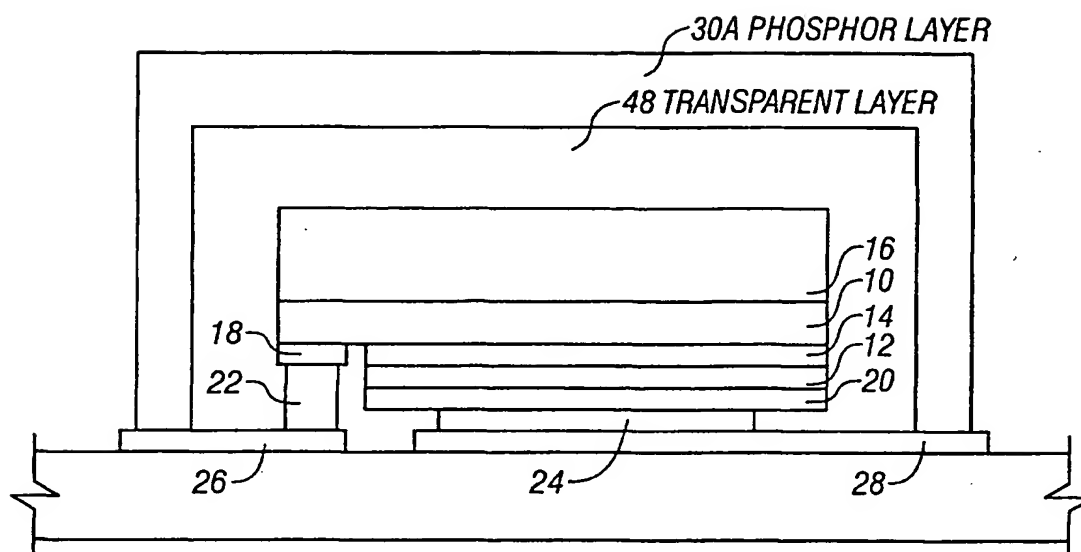


FIG. 6

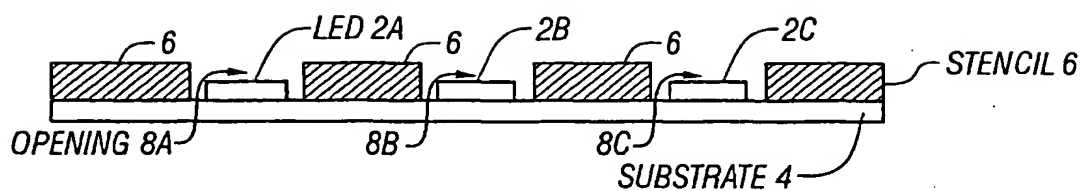


FIG. 3A

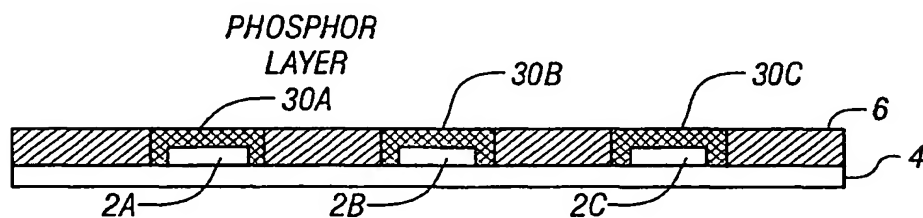


FIG. 3B

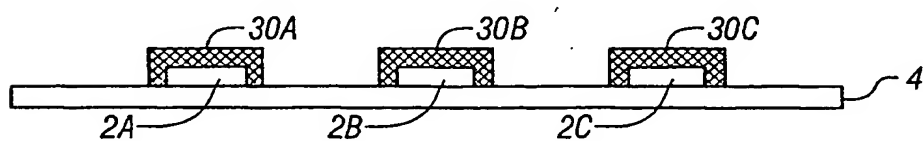


FIG. 3C